EXAMPLE 3

Partial Boiling in Micro-channel

[0232] A stainless steel device was fabricated to test partial boiling in micro-channels. The device was made by welding two stainless steel plates with milled micro-features that on assembly made micro-channels. Stainless steel plate **1** combined with stainless steel plate **2** to produce micro-channel flow paths. The total length of the plates and hence the micro-channels was 60 cm. The total width of the plates was 1.5(3.8 cm). The nominal thickness of both the stainless steel plates is 5/16 (8 mm). A chamfer was made at the outer edge of the plates to facilitate welding of the plates.

[0233] The micro-channels formed by combination of the two plates had cross-sectional dimension 0.030×0.018as shown in **FIG. 1**. The length to hydraulic diameter ratio was 1067. The micro-channels were separated by a metal wall of thickness 0.018. A total of 14 such micro-channels were formed. Holes were drilled in the stainless steel plates along the length of the micro-channels (both 0.8 cm×60 cm face) as shown in **FIG. 9**.

[0234] The purpose of the holes was to insert thermocouples and estimate heat flux using the measured temperature. The diameter of all the holes is 0.022and Type K 0.020thermocouples were used for temperature measurements. **FIG. 13** shows the schematic of layout of thermocouples on the stainless steel plate.

[0235] Thermocouples were located at total of 9 locations along the length of the micro-channel (60 cm direction) on both stainless steel plates. The distance between each location is 2.95. At locations 1 to 9, two thermocouples are placed at each location, both going 0.75deep into the stainless steel plates. At each of these locations, the two thermocouples were located 0.01from the edge of the plates as shown in View I-I in **FIG. 10**.

[0236] At locations 1, 5 and 9, four additional thermocouples were placed. These thermocouples went 0.30deep into the plate and were offset from 0.75deep thermocouples by a distance of 0.04as shown in **FIG. 2**. At each of these locations (1, 5 and 9), two thermocouples were placed on the same side of 0.75deep thermocouples while remaining two thermocouples were placed on opposite side as shown in View II-II. The tub-like header and footer were dimensionally identical and were designed for uniform flow distribution of inlet flow.

[0237] Two strip heaters on 60 cm length and 3.8 cm width were placed on both sides of the welded plates as shown in **FIG. 9**. These heaters provide heat to the fluid in the micro-channels for boiling. The test loop to test the performance of the device is shown in **FIG. 11**. The test loop was a closed loop system. Water was used as a fluid and was also referred as coolant occasionally. The pressure of system was maintained 507 psig at the inlet of the device. The preheater heated the water to saturation temperature. Any vapor generated was removed by a separator at the inlet of the device. Heat was provided to the fluid using the strip heaters to partially boil the fluid. The partially boiled fluid was then sent through the condenser to cool it down below condensation temperature and send it back to pump where water was pressurized again before sent to the preheater, thus forming a closed loop system. An inline pressure controller was installed to regulate the system pressure.

[0238] The tests were performed at a flow rate of 12 ml/min/channel. A steady state operation of partial boiling was been achieved in the extraordinarily long micro channel array with water as coolant, as shown in **FIG. 12**. The device was operated at various heat flux rates from the strip heaters (as indicated in **FIG. 12**) and a constant temperature was obtained near the walls of the channel indicating successful partial boiling. The Boiling number at q"=5.8 W/cm^2 is 7.2×10^{-5}. The SR number is calculated to be 7.8×10^{-10}. The variation of vapor quality at the outlet of the device is shown in **FIG. 13**.

[0239] The variation of wall temperature profile along the length of the channel with inlet mass flow rate is shown in **FIG. 18**. As we can see from the figure, at flow rates=12, 10 and 7.9 ml/min/channel, the wall temperature is maintained in a tight temperature band of 3° C. indicating partial boiling in the channels. However when the flow rate is reduced to 5.7 ml/min/channel, the wall temperature starts increased indicating a complete vaporization in the channel.

[0240] The back pressure regulator used on the outlet of the test system had a 25 second period of oscillation with 2 psig amplitude. The gentle oscillations shown on the performance curves result from the back pressure regulator and not from the partial boiling process. The very small pressure variation (less than 2 psi) demonstrated stable performance in time.

[0241] The inventive processes should be stable. Stability here for a microchannel boiling process is defined as follows: partial boiling is considered stable when only low fluctuation amplitude variations in measured flow pressure equal to or less than 5% of the average absolute operating pressure of the system and a characteristic oscillation frequency of a ratio less than 20 (peak amplitude to noise amplitude). Thus for instance, the maximum peak-to-peak oscillation in pressure is 5 psid and the average operating pressure is 505 psig =520 psia. Therefore the oscillation to operating pressure ratio is 5 psid /520 psid=0.96%<5%. Furthermore, the accuracy of the pressure tap transducers used in this experiment were at most 0.5% of full pressure loading at 1000 psia or 5 psi and thus the peak to noise ratio=5 psid /5 psi=1<20.

[0242] Channel aspect ratio (ratio of width to height) is another consideration for stable, partial boiling. Channels with low aspect ratio experience more bubble confinement during the onset of bubble nucleation at the surface. This in turn leads to conditions that promote bubble coalescence ultimately resulting in Taylor bubbles or slugs of vapor that occupy nearly the entire cross-sectional area of the channel. These conditions can lead to unstable two-phase flow systems. High aspect ratio channels, on the other hand, provide a greater degree of freedom in the channel width dimension to expand without encountering another nearby bubble before surface detachment. Furthermore, the persistence (lifetime) of Taylor bubbles (vapor slug) is dependent in part upon the geometry of the bubble. Cylindrical bubble slugs that, for instance, occur in tube flow are regarded as very stable and will persist for long periods of time. Taylor bubbles forced to take place in high aspect ratio channels will have a large relatively flat surface (such as a bubble squeezed between two parallel plates). The flat surface of the bubble cannot take on a more stable cylindrical or spherical shape which minimizes free surface energy, and therefore